

Hot Flashers and He Dwarfs in Galactic Globulars

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ABSTRACT

Context. We revisit the evolutionary scenario for Hot Flasher low-mass structures, where mass loss delays the He flash till the initial phases of their White Dwarf cooling sequence.

Aims. Our aim has been to test the theoretical results vis-a-vis different assumptions about the efficiency of mass loss.

Methods. To this purpose, we present evolutionary models covering a fine grid of masses, as obtained assuming a single episode of mass loss in a Red Giant model of $0.86 M_{\odot}$ with $Z=0.0015$.

Results. We find a reasonable agreement with previous evolutionary investigations, showing that for the given metallicity late Hot Flashers are predicted to cover the mass range $M=0.4975$ to $M=0.4845 (\pm 0.0005) M_{\odot}$, all models igniting the He-flash with a mass of the H-rich envelope as given by $M_e=0.00050 \pm 0.00002 M_{\odot}$. The ignition mechanism is discussed in some details, showing the occurrence of a bifurcation in the evolutionary history of stellar structures at the lower mass limit for He ignition. Below such a critical mass, the structures miss the He ignition, cooling down as a Hot Flasher-Manqué He White Dwarf. We predict that these structures will cool down, reaching the luminosity $\log L/L_{\odot}=-1$ in a time at the least five times longer than the corresponding cooling time of a normal CO White Dwarf.

Conclusions. On very general grounds, one expects that old stellar clusters with a sizeable population of Hot Flasher should likely produce at least a similar amount of slow-cooling He White Dwarfs. According to this result, in a cluster where 20% of Red Giants escape the He burning phase, one expects roughly twice as White Dwarfs than in a normal cluster where all Red Giants undergo their He flash

Key words. Stars: evolution, Stars: White Dwarfs, Stars: mass loss

1. Introduction

Over the last decades the evolution of low-mass stellar structures has been the subject of a large amount of investigations, aimed at constraining the evolutionary status of stars in old stellar systems, such as Galactic Globular Clusters. Since long time we know that present Globular Cluster stars are expected to leave their Main Sequence to climb along the Red Giant Branch (RGB) till the onset of the He-flash. After the phase of central (Horizontal Branch) and shell (Asymptotic Giant Branch) He burning phases, they will eventually cool down under the form of Carbon-Oxygen (CO) White Dwarfs (WDs).

In this context, the occurrence of extended "Blue Tails" in the Horizontal Branches (HB) of several Galactic Globulars has already been understood in terms of RGB structures which have lost the large majority of their

H-rich envelope before igniting He to become HB stars. Castellani & Castellani (1993; but see also Castellani, Degl'Innocenti & Pulone 1995) found that, for extreme mass loss, there are stellar models which fail to ignite He at the tip of the RGB, but undergo a late He-flash during the contraction toward their He-WD structure or in the early stages of the WD cooling sequence. Similar structures are now known in the literature as "Hot He-Flashers" (HFs). Even larger mass loss will prevent the He ignition, definitively producing He White Dwarfs.

Hot Flashers have been extensively investigated by several authors. D'Cruz et al. (1996) made use of Reimers (1975, 1977) formula for mass loss, taking the efficiency parameter η_R as a free parameter to explore the range of mass-loss producing HFs for selected assumptions about the star metallicity. Sweigart (1997) discovered that when the He-flash occurs along the WD cooling sequence ("late" HFs), then convection is expected to reach the H-rich envelope, enhancing He and Carbon abundances in the stellar atmosphere and driving strong H-flashes. Brown et al. (2001) adopted again the Reimers formalism to ex-

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* It is with deep sorrow that we announce the death of Vittorio Castellani, who passed away on May 20, 2006.

plore the occurrence of late HF for the metal abundance $Z=0.0015$, in connection with observational evidence for extremely hot HB stars in the Galactic globular NGC2808. Quantitative estimates of the mixing driven by the He-flash have been finally presented by Cassisi et al. (2003), who were able, for the first time, to follow in detail the growth of such an instability in late HFs.

In this paper we revisit the HF theoretical scenario but adopting different assumptions concerning the mass-loss mechanism. On this basis we will present and discuss new evolutionary results, focusing the attention on the stellar structures marking the transition between late HF and bona fide He WD.

2. The models

All the papers quoted in the previous section have investigated the occurrence of HF using the Reimers mass-loss parameter η_R as a free parameter to govern the efficiency and, thus, the amount of mass loss. However, among these investigations there are subtle differences. As a matter of fact Castellani & Castellani (1993) took into account mass loss till the onset of the He-flash, whereas D’Cruz et al. (1996) neglected mass loss when the mass of the H-rich stellar envelope reached the value $M_e = 10^{-3}M_\odot$. Brown et al (2001) also stopped the mass loss, but when the structure moved away from the RGB by $\Delta\log T_e[K] = 0.1$.

Here we notice that, at least in principle, these differences can have sizeable consequences on the final structures. Data in Table 4 of Castellani & Castellani (1993) disclose that, according to Reimers’s formulation, after leaving the RGB a HF model is expected to loose an amount of mass of the same order of magnitude of the value of M_e at the onset of the flash (M_e^f). In turn, theoretical predictions on M_e^f are at the basis of relevant observational constraints, since the minimum value of M_e^f governs the maximum effective temperature that can be reached by normal Zero Age Horizontal Branch (ZAHB) models: the maximum effective temperature increases when M_e^f decreases (see, e.g., the discussion in Castellani, Degl’Innocenti & Pulone 1995). It appears thus of obvious relevance to investigate in detail theoretical predictions on such a critical issue.

However, in spite of the different assumptions about mass loss, all the investigations we are referring to find rather similar values for M_e^f . This interesting evidence is supplemented by the result by Brown et al. (2001, but see also D’Cruz et al. 1996) who found that, for a given original chemical composition *late HFs have all exactly the same value of M_e^f* . Such a behavior suggest that M_e could be the parameter governing the onset of the flash in HF structures, independently of any assumptions about the mechanism and the efficiency of mass loss. Such a suggestion can be supported by inspection of evolutionary data for HF structures, as given in the already quoted Table 4 in Castellani & Castellani (1993). Stars leaving the RGB are still supported by CNO H-shell burning. Only when approaching the final (“critical”) value of M_e the CNO

Table 1. Selected physical quantities for stellar structures at the He flash ignition as a function of the mass after the episode of mass loss. Masses and luminosities are in solar units.

M	$\log L^f$	$\log T_e^f$	M_e^f	M_e^f
<i>RG Flash</i>				
0.5301	3.3915	3.6221	0.49755	0.03255
0.5200	3.3905	3.6287	0.49735	0.02265
0.5100	3.3885	3.6388	0.49715	0.01285
0.5028	3.3856	3.6580	0.49663	0.00617
<i>HF-Transition</i>				
0.5000	3.1639	4.8936	0.49914	0.00086
0.4980	3.1745	4.9968	0.49723	0.00077
<i>Late HF</i>				
0.4970	0.5872	4.6490	0.49652	0.00048
0.4950	0.1837	4.5160	0.49451	0.00049
0.4910	-0.1295	4.4438	0.49050	0.00050
0.4901	-0.1411	4.4388	0.48960	0.00050
0.4890	-0.2653	4.4122	0.48848	0.00052
0.4880	-0.2933	4.4038	0.48748	0.00052
0.4870	-0.3731	4.3914	0.48649	0.00051
0.4860	-0.4066	4.3907	0.48549	0.00051
0.4850	-0.4623	4.3917	0.48448	0.00052

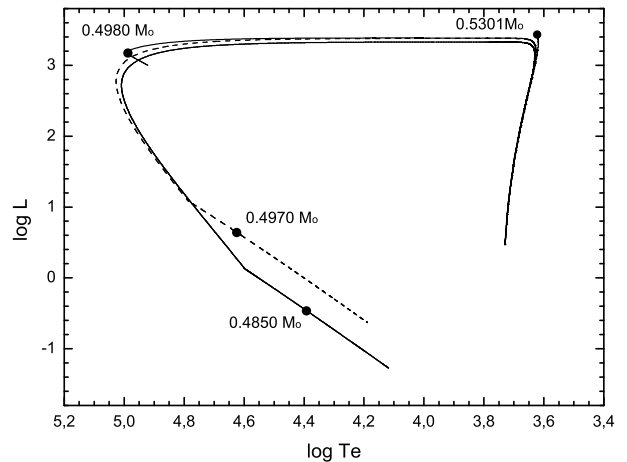


Fig. 1. The evolutionary paths of selected models, for the labeled values of the total stellar mass. Dots show the location of the He-flash as given in Table 1 (see text for more details). L is in fraction of L_\odot , T_e is in [K].

burning starts decreasing and the stellar core experiences the final contraction leading the structure either to a late He-flash or to the final cooling as a He-WD. Here we suggest to regard the quoted time sequence as an evidence that in late HFs there is a critical minimum M_e^f value supporting H-shell burning. When this minimum is reached, the H-shell switches-off, causing the core contraction and the switch-on of the He-flash. As well known, the contrary occurs in normal RGB structures experiencing the He-flash.

To investigate this scenario we decided to get rid of any interplay between the late evolution of HF models and mass-loss rates, producing suitable HF progenitors

by peeling-off a model during an early stage of his RG evolution and thus following the evolution of the structure assuming no further mass loss. One may notice that a similar procedure has been already adopted by Serenelli et al. (2002). All models have been computed assuming an initial helium abundance $Y=0.23$ and a solar scaled heavy-element abundance $Z=0.0015$, i.e., the same original composition adopted by Brown et al. (2001). If not otherwise stated, in the following we will refer to HF progenitors as obtained by applying suitable mass loss in a $0.86 M_{\odot}$ RG structure, when $\log L/L_{\odot}=0.49$ and mass of the He core $M_c = 0.16 M_{\odot}$.

Table 1 gives selected physical quantities for a sample of models experiencing the He-flash. Left to right one finds the mass of the evolving star and, in the order, the luminosity, the effective temperature, the mass of the He-core and the mass of the H-rich envelope at the He flash ignition. As already known, one finds that decreasing the stellar mass the ignition of the He flash moves from the RG branch first to the luminous structures crossing the HR diagram toward the WD cooling sequence (transition HF) and then to models igniting He along the cooling sequence itself, down to $\log L/L_{\odot} \sim -0.5$ (late HF: LHF). After the He-flash, all the LHF structures have been found to experience the mixing episode and the explosive burning of H already discussed by Brown et al. (2001) and Cassisi et al. (2003).

The development of the He-flash in HF structures deserves some further comments. As usual (see, e.g., Sweigart & Gross 1976), for structures experiencing the He-flash either at the RG tip (RG Flash) or during the crossing of the HR diagram toward the cooling sequence, data in Table 1 refer to the model where the output of the 3α reaction has reached $100 L_{\odot}$. However, for LHF the identification of the He "flashing" model is less straightforward, since the He ignition has a rather long evolutionary history. Taking as an example the $0.4910 M_{\odot}$ model, the threshold of $L_{3\alpha} = 100 L_{\odot}$ is reached along the cooling sequence at $\log L/L_{\odot}=0.52592$. However, the structure keeps cooling, whereas the efficiency of He burning increases, and the maximum of the 3α production ($L_{3\alpha} = 9.2 \times 10^9 L_{\odot}$) is reached only when $\log L/L_{\odot} = -0.1295$.

According to such an evidence, we decided to list in Table 1 data for LHF models at the first maximum of the He-flash. Fig. 1 reports the evolutionary paths of selected HF models. As shown in that figure, in LHF structures the onset of the He-flash is witnessed by a clear discontinuity in the slope of the cooling track. However, the flash attains its maximum after a not negligible evolution along the new cooling curve. As already found by Cassisi et al. (2003), after the flash the structure keeps cooling, until the mixing event causes the H-flashes which drive the star toward their stage of quiescent central He burning.

Inspection of the evolutionary results reveals the reason why below the critical mass $M = 0.485 M_{\odot}$ the stars miss the He flash: decreasing the mass of a Hot Flasher the contraction driving the efficiency of 3α reactions starts in

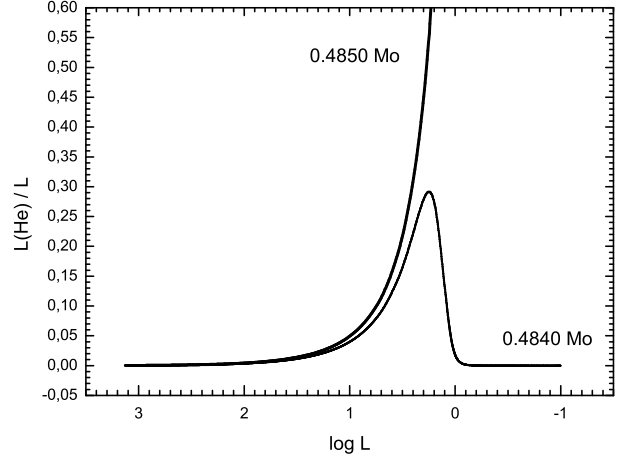


Fig. 2. The He burning contribution to the star luminosity for the two cooling structures at the transition between Hot Flashers and He White Dwarfs. L is in fraction of L_{\odot}

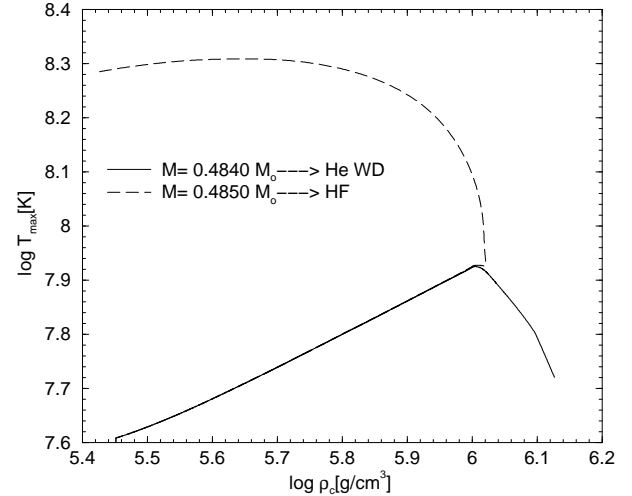


Fig. 3. The run of the maximum (off center) temperature versus the central density for the two cooling structures at the transition between Hot Flashers and He White Dwarfs.

more advanced phases along the cooling sequence, progressively approaching the region where structures are strongly affected by neutrino emission. Fig. 2 shows the contribution of 3α reactions to the star luminosity for the two cooling models of $M = 0.4850$ and $0.4840 M_{\odot}$, i.e., just above and below the lower limit for He ignition, at the transition between Hot Flashers and He White Dwarfs. One finds that just below the critical mass the structure starts attempting the final He ignition, but the neutrino emission soon overcomes the output of nuclear energy, cooling down the stellar interior, halting the ignition mechanism. Fig.3 shows the maximum off center temperature as a function of central density for the same two models. As already found when discussing the critical stellar mass for carbon ignition (see Fig. 4 in Castellani et al. 2003), even in the case of He ignition one finds the clear

evidence for the predictable "bifurcation" in the evolution of the physical conditions in the stellar interiors.

Data in Table 1 deserve several comments. One finds that all the LHF reach the flashing phase with a quite similar envelope mass, namely $M_e = 0.00051 \pm 0.00001 M_\odot$. Such an evidence reinforces the suggestion that M_e should be the parameter governing the onset of the late He-flashes. At the same time, this result confirms the evolutionary scenario presented by Brown et al (2001). Only the mass of the LHF envelopes is in our models slightly smaller, 0.00051 against $0.0006 M_\odot$, perhaps for small differences in the input physics (but see also Cassisi et al. (2003) who found $M_e = 0.00055 M_\odot$). Here we notice that the suggested connection between the H-burning switch-off and the onset of late He-flashes gives a natural explanation of the dependence of M_e^f on metallicity (D'Cruz et al. 1996), for which an increase in the metallicity of HF structures causes a decrease in the final pre-flash M_e . This appears indeed in agreement with the often reported evidence that an increase in the metallicity decreases the minimum mass of the envelope supporting H-shell burning (see, e.g., Castellani et al. 1994).

3. Hot Flashers and He White Dwarfs

According to our computations, one finds a lower mass limit for the He-flash $M = 0.4850 M_\odot$: a decrease of this mass by only $0.001 M_\odot$ implies that the stellar structure does not succeed in igniting He, definitely cooling down as a He WD. Fig.4 shows the evolutionary paths for some of these He WD models. As already discussed in Castellani et al. (1994), one finds that, below the critical mass for the onset of the He flash, the more massive WDs are predicted to cool down quietly at least down to $\log L/L_\odot = -1.0$. However, when the WD mass is decreased, the models show below $\log L/L_\odot \sim 0$ the progressive contribution of the H-reignition which in the $0.3 M_\odot$ eventually drives the ignition of strong CNO flashes.

One might notice that the predicted LHF cover a restricted but not negligible range of masses, namely $\Delta M \sim 0.012 M_\odot$, against the mass dispersion by $\sim 0.02 M_\odot$ often taken as representative of normal HB (Rood 1973). Thus the production of a substantial amount of HF does not require a too fine tuning of the mass loss mechanism. This supports the suggestion by Brown et al. (2001) for which LHF could be at the origin of the hottest group of HB observed in the globular NGC2808, as well as of similar structures in ω Cen (Moehler et al. 2004). As already discussed by D'Cruz et al. (1996), there are no physical basis for predicting the efficiency of mass loss. However, one can hardly believe in a distribution of mass loss producing LHF's but no WDs. On the contrary, the occurrence of HF's likely implies the occurrence of at least a similar amount of stars which miss the He flash, cooling down as He WDs.

According to their larger heat capacity, we know that He WD evolve more slowly than CO WD do, the cooling law depending -for each given WD mass- on the mass

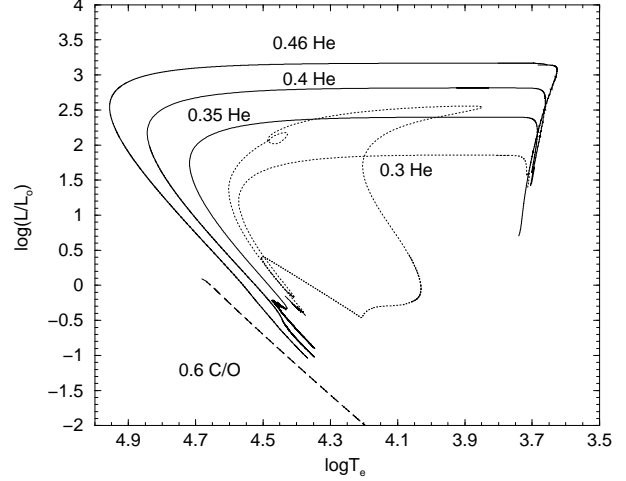


Fig. 4. Evolutionary paths of selected HF-Manqué He WD models for the labelled values of the stellar mass. The cooling sequence of a $0.6 M_\odot$ CO WD is reported for comparison.

Table 2. Selected physical quantities for stellar structures cooling down as He White Dwarfs. Masses and luminosities are in solar units, cooling times t in Myr.

M	$\log L$	t	M_c	M_e
0.4840	0.0000	3.8	0.48342	0.00058
	-1.0000	92.9	0.48352	0.00048
0.4600	0.0000	2.1	0.45642	0.00358
	-1.0000	111.4	0.45653	0.00347
0.4000	0.0000	0.8	0.39834	0.00166
	-1.0000	174.2	0.39859	0.00141

of the H rich envelope as well as on the efficiency of element diffusion mechanisms. Having established within $10^{-3} M_\odot$ the minimum HF mass, we have simultaneously fixed, within the same uncertainty, the maximum mass allowed for He dwarfs together with a firm predictions about the mass of the H-rich envelopes in the various cooling structures. It is obvious interesting to investigate the cooling law for these structures in the range of masses just below the HF interval. This appears of particular relevance since current investigations have already detected an unsuspected large amount of Hot Flashers candidate in clusters like NGC2808 (Castellani et al. 2006) and ω Cen (D'Cruz et al. 2002), but also a huge amount of WDs in the latter cluster (Monelli et al. 2005).

Table 2 gives the cooling times for selected HF-Manqué He WDs at the two luminosities $\log L/L_\odot = 0.0$ and -1.0 together with the corresponding values of the masses of the He-core and of the H-rich envelope. Evolutionary times are computed starting from the models reaching the maximum effective temperature after leaving the RG branch. Inspection of evolutionary times in Table 2 reveals that at the limit $\log L/L_\odot = -1$ HF-Manqué He WD should have a minimum cooling age of the order of 90 Myr, which increases when the mass decreases. Thus, above the quoted

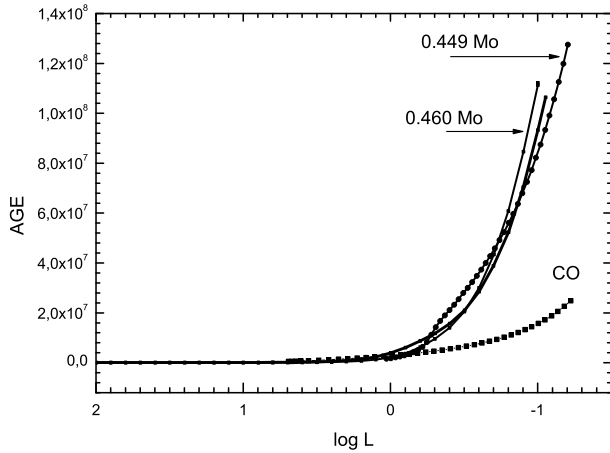


Fig. 5. The cooling ages versus the WD luminosity for our most massive He WD model ($0.4840M_{\odot}$: heavy line) compared with the less massive model $0.4600M_{\odot}$, the $0.449M_{\odot}$ with element diffusion (Serenelli et al. 2002) and a $0.5M_{\odot}$ CO WD (Prada Moroni & Straniero 2002). L is in fraction of L_{\odot} and AGE is in years.

luminosity limit HF-Manqué He WD have a lifetime of the same order of magnitude or larger than typical HB stars.

However, one must notice that models in Table 2 do not account for the effect of element diffusion. According to current estimates, the main effect of diffusion in He WDs is to drive the occurrence of strong CNO flashes which can deeply affect the age-luminosity relation (Althaus, Serenelli & Benvenuto 2001a, 2001b). However, and luckily enough, even if diffusion is taken into account He WD models just below the LHF mass limit seem to escape such an instability, cooling quietly down toward their fainter evolutionary phases (Serenelli et al. 2002). Thus, element diffusion should have only minor effects. This is confirmed by data in Fig. 5, where we compare the age-luminosity relation for two selected models from our sample with a similar model ($M = 0.449M_{\odot}$) presented by Serenelli et al (2002) for $Z=0.001$ and with diffusion taken into account. As a whole, one may conclude that age given in Table 2 should give, at least, a reasonable order of magnitude for WD ages.

Comparison with the age-luminosity relation for a CO WD ($M = 0.5M_{\odot}$), as given in the same figure from Prada Moroni & Straniero (2002), gives an impressive evidence of the large predicted differences between HF-Manqué He WD and CO WD, supporting some relevant considerations. One can easily predict, e.g., that in a cluster where 20% of RG escape the He burning phase, above $\log L/L_{\odot} = -1$ one expects roughly twice as WD than in a normal cluster where all RG undergo their He flash. It follows that WD counts above the quoted luminosity limit can give relevant information on the abundance of HF-Manqué He WDs.

4. Summary and conclusions

In this paper we have addressed the problem of Hot Flasher, investigating in details the predicted evolutionary behavior of low mass stars with $Z=0.0015$ after an episode of mass loss during their RG evolution. We found that stellar masses in the range $0.485 \leq M \leq 0.497M_{\odot}$ experience the He flash (and the explosive H-reignition) during their WD cooling phase, when the residual H shell burning has reduced the H-rich stellar envelope down to $M_e \sim 0.0005M_{\odot}$, independently of the mass of the model. Such a result appears in reasonable agreement with theoretical predictions given by Brown et al (2001) for the same metallicity, the small difference ($M \sim 0.0005$ against $0.0006M_{\odot}$) being likely the effect of small differences in the adopted input physics. Supporting, in turn, the evidence that the mass of the H-rich envelope plays a critical role in the onset of the delayed He flashes.

According to this result, we are also predicting the structural parameters needed to evaluate the evolutionary times of structures below the lower mass limit for He ignition, which will definitely cool down as He WD. We find that these He WD will reach the luminosity $\log L/L_{\odot} = -1$ in a time about 5 times longer than normal Carbon-Oxygen WDs do, giving a detectable contribution to the abundance of WD above such a luminosity if and when a not marginal fraction of RG stars escape the He ignition.

For the sake of completeness, one has finally to advise that the current scenario slightly depends on the luminosity of the RG models undergoing the mass loss episode, since peeling off RG structures either before (as in the previously reported computations) or after the first dredge up gives HF progenitors with different He abundances in the stellar envelopes. Numerical experiments for our $0.86M_{\odot}$ models have shown, e.g., that when the models is stripped after the dredge up ($\log L/L_{\odot} = 1.48$, $M_c = 0.24M_{\odot}$) the lower mass limit for LHF moves from 0.485 to $0.491M_{\odot}$, with LHF models characterized by slightly smaller H-rich envelopes, as given by $M_e^f = 0.00048M_{\odot}$. As a whole, these appear as marginal differences, not affecting the theoretical scenario we are dealing with.

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